Renewable and Sustainable Energy Reviews 18 (2013) 154–164

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Potential of bioenergy production from industrial hemp (*Cannabis sativa*): Pakistan perspective

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ARTICLE INFO

Article history:
Received 26 October 2011
Received in revised form
9 October 2012
Accepted 10 October 2012
Available online 8 November 2012

Keywords:
Bioenergy
Industrial hemp
Sustainable development
Pakistan

ABSTRACT

Pakistan is facing severe economical crunch due to continuously growing gap between energy demand and supply. The shortage in power and gas supply has already halted many industrial sectors such as textile, small and medium enterprises and local transportation. The government has spent US $ 9 billion on energy import during 2008–2009 to fulfill current energy requirements. Indigenous energy resources, mainly fossil fuels, are already being exploited at their maximum. Besides these short term steps, energy demand is expected to double during next decade. Thus, renewable and sustainable energy resources, such as biomass, needs to be exploited so that a sustainable energy mix could be employed to ensure energy security. Industrial hemp (*Cannabis sativa*) has been successfully investigated for its potential to be used as a renewable feedstock for the production of biofuels. Hemp is an environmental friendly and low cost feedstock which grows wildly in most parts of Pakistan. Thus, hemp can be grown as a potential energy crop in Pakistan to meet its energy requirements by producing various kinds of biofuels. This sustainable feedstock will help the country to reduce its energy import bills, and ensure sustainable energy supply.

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1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.10.019

1. Introduction

Energy is considered one of the most important commodities of life in the present age. Secure and sustainable energy supply ensures socio-economic development of any country. However, global energy resources, mainly fossil fuels, are under immense pressure due to over exploitations in order to meet the requirements of growing human population. Moreover, energy demand has increased tremendously due to expansion in global economy [1]. Fossil fuels are used as a prime energy source to fuel the global economy. Energy demand is expected to double within a decade, whereas fossil energy resources are facing a threat of rapid depletion in future. This situation has not only raised the concerns about an uneconomical but also an insecure energy supply in future. Besides the risk of depletion, fossil fuels are also associated with the release of greenhouse gases (GHGs) such as CO_2 gas, which is usually held responsible for global warming and climate change [2]. Thus, non renewable fossil fuels are not reliable option on long term basis due to their scarcity and environmental risks [3]. These two challenges, energy resource depletion and GHG emissions, can only be overcome by diversifying conventional fuel resources with renewable and sustainable energy resources.

Biofuels can be a sustainable alternative to the conventional fossil fuels. Several types of biofuels (bioethanol, biodiesel, biogas and biohydrogen) can be obtained using biomass feedstocks which are environment friendly and sustainable in nature [4]. Generally, grain and seeds from crops like corn, wheat, sugar cane, and cereals are used as feedstocks to produce bioenergy [5]. These feedstocks (directly) and their arable land (indirectly) compete with other food commodities and pose a threat to food security. Thus, lignocellulosic biomass (LCB) is preferred as a feedstock for bioenergy over grain based energy crops because LCBs increase arable land use efficiency and do not compete with food crops. However, those LCBs are usually preferred which achieve higher yield per hectare [6]. Soil health is an important factor that increases the yield of energy crops, and it can be sustained by adopting crop rotation. Only few such crops are available which can assist to maintain soil fertility through crop rotation and ensure sustainable production of bioenergy feedstock [7]. Thus, LCB feedstock is an innovative alternative to conventional food crops for the production of biofuel. LCB offers several advantages such as CO_2 neutral, no competition with food crops and abundant availability [8,9]. Besides many promising advantages, LCBs possess highly crystalline recalcitrant structure which makes it difficult to extract fermentable sugars for bioethanol production without prior pretreatment [10]. Pretreatment step inherits some technical and economical limitations in the biofuel production from LCB [11]. Furthermore, feedstock cost also affects the economics of biofuels production, and it depends on agricultural requirements of biomass cultivation [12].

Industrial hemp (*Cannabis*) is a C3 plant that is classified into the family of Cannabaceae. It is subdivided into three main types such as *C. sativa, C. indica,* and *C. ruderalis. C. sativa* is characterized by long, thin flowers and spiky leaves [13]. Industrial hemp has emerged as a potential energy crop along with several advantages. Hemp exhibits many salient features like low feedstock cost, high biomass content [14], high land use efficiency, higher dry matter (DM) yield, low nutrients requirement, no/zero pesticide demand and can improve soil health with organic matter [15]. It can be effectively grown in diverse climates and can be used in organic crop rotation [16]. Hemp biomass (HB) produces high biomass as well as hemp oil, therefore, it can be used for the production of bioethanol, biogas, biohydrogen, solid fuel, and biodiesel [14].

To the best of our literature review, there has been no published review explaining the potential of HB for bioenergy production. HB grows as a wild plant on large area in Pakistan. The primary aim of this paper is, therefore, to review the potential of HB for bioenergy (bioethanol, biodiesel, biogas, biohydrogen) production and to use as solid fuel. Moreover, HB prospective cultivation in Pakistan, as an energy crop, in order to meet current and future energy demands has also been explored and discussed.

2. Hemp biomass

Industrial hemp is usually cultivated to obtain its fibers. Hemp carries many features which make it an ultimate choice for biomass and bioenergy production. These traits include drought and microbial resistance, high biomass yield [17], no requirement for herbicides [18,19], almost half of the requirement for nutrients than maize [20], growth in contaminated soil [21], suppression of soil borne pathogens [22] and usage for crop rotation [18,23]. Hemp produces a higher amount of biomass due to its higher growth rate (50 cm/month) and it is rich in leafage. These characteristics make hemp dominant over other weeds. Excessive leaves of hemp are lost during harvesting season which work as fertilizer to improve soil quality [24]. Resultantly, hemp pose almost zero environmental impacts compared with other LCB feedstocks grown for biofuel production. Piotrowski and Carus [25] have carried out and reported a detailed ecological assessment of hemp biomass [25]. HB contains higher carbohydrate contents and relatively lower amount of lignin which make it an ultimate environment friendly and renewable choice for bioenergy production [26]. Hemp is used for many industrial and domestic applications as well. The detail of these applications of HB [27–42] is presented in Table 1.

2.1. Structure and composition

The properties of hemp plant vary from part to part (top, middle section and base). Fresh green hemp fiber is composed of cellulose (55%), hemicelluloses (16%), pectic sub stances (18%) and lignin (4%). The fiber cells are bound with middle lamellae in bundles. Parenchyma cells of cortex separate these fibrous bundles [43]. Vascular cambium in hemp provides additional secondary fibers to its stem which increase the stiffness of stem, and assist the plant to erect itself with a small diameter and lengthy stem [44].

The stem can be separated into two parts as bast fiber (35%) and a woody core (65%) [45,46]. The bast fiber contains a higher content of cellulose (57–77%) compared to other agriculture crops like corn stover [47] and wheat straw [48], and 5–9% lignin content [45]. However, woody core contains less amount of

Table 1
Applications of hemp biomass in domestic and industrial sectors.

Applications	Type	Ref
Textile	Fiber	[28]
Pulp	Cellulosic material	[28–29]
Paper packaging	Teabags and coffee filter	[30]
Wax paper	Match packaging	[31]
Cigarette paper	Cigarette packaging	[32]
Electrical insulation paper	Insulation	[33]
Composite material	Fiber reinforced	[34]
Construction material	Fiber insulation	[35]
Fuel	Solid fuel	[36]
Medical treatment	Narcotic drug	[37–39]
Food	Oil and protein	[40]
Cosmetics	Oil	[40]
Synthetic plastic	Industries	[41]
Fiberglass	Automotive	[42]

cellulose (40–48%) and higher amount of lignin (21–24%) compared with bast fiber [43]. Middle and lower parts of the stem contains relatively higher quantity of cellulose than other parts of HB. Contrary to that, hemicellulose is located in upper part of HB stem. Hemicellulose concentration entirely depends on harvesting time of HB. Early harvesting causes immature plant biomass and hence, it leads to higher hemicellulose content in the stem [49].

Hemp has been reported to be more stable than wheat straw. Hemp belongs to herbaceous dicotyledonous species. These species consist of highly lignified xylem ring which is present in their stem. This xylem ring makes HB recalcitrant whereas the remaining tissues, either present at the centre or in the periphery of the stem, can be degraded easily. Hemp exhibits a flexible structure after the release of lignin from xylem [50]. Lignin is uniformly distributed among various parts of HB (top, middle and base sections), however, its content may vary in different varieties of hemp [49].

2.2. Cultivation

Hemp is a C_3 crop which is usually cultivated for its bast fiber [51]. It is native plant to Central and South Asian countries evident for last 5000 years [52,53] like Pakistan, India, Russia, China, and Iran [54]. It had also been cultivated in European countries like Sweden before 1960, but its cultivation was restricted due to the presence of phyto-chemical drug component THC (*d*-9-tetrahydrocannabinol) thereafter [55]. Some varieties of hemp, with a THC content <0.2–0.3% (w/v), assumed their cultivation in 2007 after the approval from EU [4]. These hemp cultivars generate approximate annual revenue of $100–200 million with an increase of $8–10 million/year only in North American market [13,56].

Hemp is a versatile crop which can be cultivated under various climatic conditions. However, weather conditions show strong effects on plant morphology. HB characteristics such as stem length and diameter, significantly depend on weather conditions as well as plant density [57]. Low plant densities may results in reduced yield and lower quality of biomass. Hemp yield is directly related to its physio-morphological features, thus, hemp plant requires special care during its breeding season. Yield can be increased by using later cultivars because they observe prolonged growing seasons. Under these conditions, cellulose quality does not get affected, however, lignin content increases rapidly after flowering [18].

Hemp crop also shows high level of heterogeneity due to variation in the growth pattern between male and female plants [58]. Flowering starts earlier in male plants. Taller plants with same sex considerably affect the growth of shorter plants [59]. This variation leads to limited yield, less resource efficiency and variable quality among hemp plants. Hemp cultivation requires almost no pesticides and small amount of fertilizers. Nitrogenous fertilizers show moderately positive impact on HB yield but its response varies for different regions and years of cultivation [18]. Pakarinen et al. [20] reported that mazie required twice the quantity of fertilizer than hemp for almost similar DM yield, whereas Poisa and Adamovics [24] found that increased nitrogen fertilization had a negative relationship with oil content of hemp seeds.

Fiber hemp yield depends on environmental conditions and cultivation pattern. Hemp yield has been reported about 20 t DM/ha in the countries with temperate climatic conditions such as Italy, the Netherlands and the United Kingdom [18,49]. Late maturing varieties of hemp are also capable to yield high DM even under cold climate conditions [18,60,61]; in the regions of Scandinavia, Eastern Europe, Canada and the USA [62]. Prade et al. [15] reported that hemp had been grown on eight hundred ha in Sweden, whereas biomass yield varied between 10 and 14.5 t DM/ha(US ton) between the South and Northern Sweden [63,64]. Hemp production in Germany approached approximately 1600 m^3/ha [65]. It has been reported that the European Union produces about 29% hemp of total world [29]. However, Tuck et al. [66] studied hemp cultivation in Europe using different prediction models which concluded that hemp cultivation would disappear from Southern Europe and shift to Northern Europe by the 2050s and 2080s.

Some other western countries like Spain [17], Ireland [36], Finland [67], Poland [68], Latvia [24,69] and USA [70] also cultivate hemp for bioenergy purposes.

2.3. Harvesting

Harvesting time of HB entirely depends on its post harvesting use. Generally, late harvesting is preferred to yield the highest biomass for biofuel production [71]. Kreuger et al. [4] investigated the effect of cultivation and harvesting time on the yield of hemp biomass. It was found that biomass yield was higher in the months of September and October, whereas non-significant difference was observed in the yield among different years. The average hemp biomass yield was 15.6 ± 1.5 t DM/ha during the months of September and October in the years of 2007 and 2008. In another research, Cappelletto et al. [49] studied the cultivation of eight varieties of hemp, and studied the effect of harvesting time on their biomass yield. It was reported that average yield of these varieties was 29.67 and 21.70 t/ha, respectively, for the months of July and August. According to the researchers, early harvesting yielded slightly higher DM contrary to other studies. No significant difference was found among various varieties for biomass yield during any harvesting time [49].

Harvesting time for hemp is significant for its use to produce biogas. High DM yield and biodegradability of hemp biomass are important factors for higher biogas yield [4]. Prade et al. [15] found that the months of September–October were optimal for hemp harvesting, when it is to be used for biogas production, with an average HB yield of 15.87 t DM/ha and 296 GJ/ha. In another study, hemp yield ranging between 10.7 and 14.2 t DM/ha was also reported for biogas production. A significant effect of harvesting time was also found on the methane yield per ha. Energy yield in terms of methane/ha was obtained 122 GJ/ha when hemp was harvested in September [69]. Prade et al. [15] reported that the months of March–April were optimized for hemp harvesting, for its use as solid fuel, with an average HB yield of 10.91 t DM/ha, and 246 GJ/ha. However, the average oil yield of hemp ranges between 0.14 and 0.70 t/ha out of seed output 0.5–2 t/ha [17].

2.4. Storage

Hemp is dried in the field in warmer areas and stored under dry conditions whereas ensiling is a preferred option for its storage in case of rainy areas. The acids produced during ensiling favor physio-chemical pretreatment of hemp biomass as catalysts, and improve the process economics for downstream processing [19].

3. Bioenergy production

Hemp biomass, like other LCBs, can be used a feedstock for several bioeregy options. A possible pathway of bioenergy production from HB is presented in Fig. 1. All of these options are discussed in the subsequent sections.

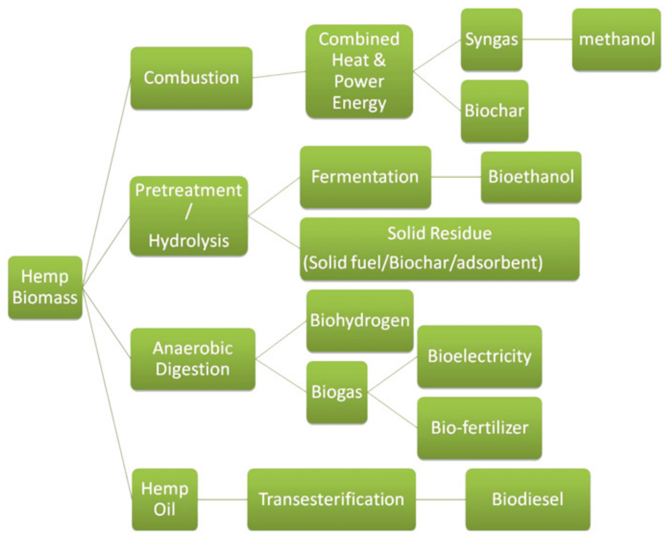

Fig. 1. Possible bioenergy pathways based on hemp biomass.

3.1. Bioethanol

Bioethanol is a prospective alternate for petroleum based gasoline. Besides sustainable fuel supply, bioethanol will also work for the reduction of greenhouse gases [72–74]. Bioethanol production can be helpful in improving rural employment and economies [75]. HB has emerged as new cheap biomass feedstock to produce bioethanol because it contains higher cellulosic and lower lignin contents [19,43–45]. Higher cellulose and lower lignin content makes HB an attractive bioresource for bioethanol production. Moxley et al. [76] reported a 96% glucose recovery from hemp hurds.

HB requires pretreatment, like other LCBs, to deconstruct the biomass and to extract fermentable sugars. These pretreatment techniques make alterations to HB structure, and make cellulose accessible to enzymes for higher yield of bioethanol [77]. These pretreatments mainly attack lignin and hemicellulosic content which facilitate enzymes to access cellulose in the biomass [11,78]. Many pretreatment options including physico-chemical, thermal, acidic, alkali based and their combinations have been vigorously explored. These pretreatments generate inhibitory byproducts which not only limit the efficacy of subsequent enzymatic process, but also increase the overall cost of bioethanol process [79–82]. The cost of pretreatment entirely depends on process conditions. Higher temperature for longer period of time is not so economical, and moreover, acids and alkalis require special vessels. Thus, many researchers are working to explore modest reaction conditions in order to improve the process economics [2].

Steam explosion is one the most investigated pretreatment techniques for LCB. Some researchers investigated the feasibility of steam pretreatment for HB in order to alter its structure. Hemp bundles observe both chemical and mechanical alteration in their structure during steam pretreatment. Steam hydrolyzes pectins and hemicellulose, makes them soluble in water. High temperature of steam softens the hemp biomass, and resultantly, fibers get disconnected from the regular structure due to sudden depressurization of steam. Steam pretreatment partially depolymerizes lignin which can be recovered for further applications. Steam pretreatment offers several advantages such as low cost, flexible, fast and well controlled operation than other options [48]. Nykter et al. [83] reported that steam pretreatment (at 185 °C for two minutes) could increase cellulose recovery from 60 to 74% from hemp fiber. Enzyme-steam integrated pretreatment yielded slightly higher cellulose (up to 78%). Sipos et al. [19] carried out steam-SO_2 pretreatment of dry hemp and hemp silage. HB impregnated with 2% SO_2 and then exposed to steam at 210 °C for five minutes. This pretreatment could yield 163 and 171 g ethanol per kg of ensiled hemp and dry hemp, respectively. Kreuger et al. [16] applied steam pretreatment of hemp stem biomass which led to produce 18.4 and 21.3 g/L bioethanol from steam pretreated slurry and solids, respectively. Steam pretreatment normally produces lower concentration of inhibitor compounds [84]. Barta et al. [85] applied steam pretreatment to non-impregnated hemp hurds at three different temperature levels 200–230 °C. This pretreatment led to an overall glucose yield of 336 g and ethanol yield of 141 g/kg of dry hurds, respectively. These yields were comparable with some other studies where other feedstocks like softwood [86], corn stover [46] and wheat straw [47], had been used as feedstock. Besides several benefits of steam pretreatment, it has been reported that steam pretreatment of hemp fiber causes more losses of DM and cellulose compared with other pretreatment methods. Various pretreatment techniques like wet oxidation, hydrothermal treatment and steam explosion showed 15–17% dry matter loss [87].

Hemp bast fiber holds high crystalline structure due to the presence of low hemicellulose contents. Gumuskaya and Usta [88] revealed that alkali pretreatment increased the crystallinity of cellulose present in HB. The crsytallinity of cellulose increased as a function of temperature from 140 to 180 °C while it decreased at 200 °C. Similar behavior was found with cooking time, crystallinity increased from 60 to 120 min while it decreased at 150 min. However, according to the researchers temperature had more pronounced effect on crsytallinity than cooking time. Moreover, organosolv pretreatment did not decrystalline hemp bast fibers and make cellulose inaccessible for downstream processing [88].

Moxley et al. [76] followed a cellulose solvent-based lignocellulose fractionation (CSLF) process to pretreat hemp hurds as described in literature [89–93]. This CSLF method was operated at moderate process conditions (~50 °C and atmospheric pressure) to decrystalize cellulose fibers, partial removal of hemicellulose and lignin content [92,93], and to avoid the formation of inhibitory compound. The application of moderate conditions could lower the operational and capital costs of the process [89]. The efficacy of cellulose solvents, applied in CSFL pretreatment of hemp hurds, was compared with other pretreatment methods (concentrated phosphoric acid, ionic liquid and concentrated sulfuric acid). Cellulose solvents did not show any significant improvement in the enzymatic digestibility of hemp hurds [94]. However, cellulose solvents mixed with an organic solvent resulted in removal of lignin and solid cellulose could be recovered from partially soluble fraction of hemicellulose [95]. This pretreatment process resulted in 20 fold higher enzymatic activity than the control, and higher sugar yields [89]. Moxley et al. [76] found that phosphoric acid concentration and reaction time were critical factors which had significant effect on overall CSFL process efficiency, whereas temperature effect was not so significant. Although CSFL process share several advantages such as moderate process conditions, high sugar yield and short hydrolysis time [89], yet it poses some bottlenecks higher cost of solvent and operational cost of recycling system [76].

High energy radiations have also been used to pretreat LCB [96–100]. The outcomes of radiation pretreatment process depend on the dose of radiations applied. Shin et al. [101] studied the effect of electron beam irradiation on hemp biomass. Electron beam radiations were applied with hot-water or sodium hydroxide solution (1%). The results showed that hemp samples, irradiated with 450 kGy after 48 h hydrolysis, showed 8–10% increase in xylose and glucose yield. Radiation pretreatment

produced radicals in the medium which caused scission of anhydro-glucose ring leading to increased carbonyl groups [99,100,102] and resulted in increased glucose and xylose contents. It was found that radiation dose did not affect glucose yield, however, xylose yield improved significantly among different level of irradiation doses [101]. Sung and Shin [103], reported that electron beam irradiation specifically targeted and degraded xylan compared to cellulose and lignin in HB, and thus, it increased enzymatic hydrolysis of xylan and yield of xylose [103].

Microbial pretreatment techniques are also used for hemp biomass. This technique involves various enzymes (hemicellulase, pectinase, xylanase and cellulase) under mild reaction conditions, however, it takes longer pretreatment time compared with other physico-chemical processes [104]. Dorado et al. [105] showed that white rot fungus *Bjerkandera* sp. strain BOS55 successfully modified hemp biomass by removing pectate materials from the surface of hemp fibers without degrading the cellulose [104].

Physical methods are also used for biomass pretreatment. Milling system can reduce crsytallinity of lignocellulosic material depending upon the type of feedstock and conditions [106]. Rotation speed and feedstock amount are considered as main factors for efficient milling process. Ouajai and Shanks [107] investigated grinding and ball milling of hemp fibers. It was found that increased milling time resulted in decreased thermal stability. Sugar yield of hemp increased from 34 to 42% as a function of size reduction [20].

3.2. Biodiesel

Biodiesel is a renewable energy option to hydrocarbon based fuels. Biodiesel can be utilized for transportation fuel and power production without any modification. Commercial production of biodiesel has already been started using various feedstock oils like soybean oil, rapeseed oil and palm oil in US, Europe and Southeast Asia [14]. It consists of monoalkyl esters of long chain fatty acids which are extracted from various renewable lipid feedstocks. These lipids are transesterified employing chemical (acid/base) conditions to yield biodiesel [108–110]. Various catalysts are used for tranesterification which include alkali, acid, enzyme and heterogeneous catalysts. Alkali catalysts are preferred in industrial production of biodiesel due to their rapid speed and ease in their scale up options. Some researchers have also worked with supercritical fluid technology to produce biodiesel in order to develop catalyst free production process [111,112]. There are several factors which affect biodiesel production such as reaction temperature, catalyst, alcohol to oil ratio, agitation speed and content of free fatty acids [113].

The production of biodiesel from edible oils is successful, but it does not seem sustainable in the long run due to its competence for food commodities. The world population will increase in the coming years, and the price of food commodities will get higher leading to food insecurity. Therefore, we need to search for some renewable and sustainable feedstocks for biodiesel production. Some researchers have investigated non edible oil sources such as Jatropha tree [114], Pongame [39] and Mahua [115] as feedstock for biodiesel production. Industrial hemp is another promising renewable and sustainable source for biodiesel production. Hempseed contains 20–25% protein, 20–30% carbohydrates, 10–15% fiber, minerals particularly phosphorus, potassium, magnesium, sulfur, calcium, iron and zinc [116], and high oil content that ranges between 26 and 38% [117]. The yield and properties of hempseed depends on geography and climatic conditions of cultivation and harvesting. Variation in the fatty acid profile and composition of hempseed oil has been observed from various locations in Pakistan [13]. The hempseed can be positively compared with conventional and nonconventional oilseed crops on the basis of oil content. It was reported that hempseed was more attractive option in terms of oil content than cottonseed (15–24%), soybean (17–21%) and olive (20–25%) grown in the United States, Brazil, China, and other Asian and European countries [118]. Hemp seed oil possesses high content of unsaturated fatty acid, thus, it is also used as a nutrition supplement [56,119,120]. Statistical analysis reveals that hemp seed oil obtained from various locations did not differ significantly (Table 2).

Li et al. [14] investigated the viability of hemp seed oil to produce hemp oil biodiesel (HOB) via base-catalyzed transesterification process. The conversion efficiency of oil was more than 99.5%, and biodiesel yield was about 97%. HOB showed comparable traits to meet ASTM 6751-09 standards. Moreover, hemp biodiesel possessed low cloud point and low kinematic viscosity. These properties made HOB a promising fuel to work under cold flow conditions. However, Ahmad et al. [113] also carried out base transesterification of hemp oil using NaOH and KOH. The crude hemp oil resulted in 0.98 and 2.11 mg/g of free fatty acid number for NaOH and KOH catalysts. However, a lower HOB yield of 75.9 and 74.3% was obtained at 0.67% concentration of catalysts (KOH and NaOH), 60 °C with a molar ration of 6:1 (methanol:oil),

Table 3
Fuel Properties of hemp oil biodiesel (B100%) according to ASTM specifications.

Biodiesel properties	ASTM specification	Li et al. [14]	Ahmad et al. [113]
Free glycerin (%mass)	0.02	< 0.005	
Total glycerin (%mass)	0.24	0.10	
Flash point (°C)	130.0 min	162	120
Kinematic viscosity 40 °C (mm^2/s)	1.9–6.0	3.48	3.83
Acid No. (mg KOH/g oil)	0.50 max	0.25	0.2
Cloud point (°C)	Report	−5	−2.5
Density 15 °C	860–900	884[a]	0.8915[b]

[a] According to EN14214.
[b] According to ASTM D5002.

Table 2
Fatty acid composition of hemp seed oil (%wt) from various locations.

Symbol	Fatty acid	Anwar[a] [13]	Li[a] [14]	Oomah [56]	Orhan [121]	Bagici [122]
Saturated fatty acids						
C16:0	Palmitic	6.68	7.25	6.6	8.53	6.53
C18:0	Stearic	2.46	2.75	2.7	3.06	2.64
Unsaturated fatty acids						
C18:1	Oleic	12.43	13.5	10.10	NR	15.21
C18:2	Linoleic	58.43	54	54.30	54.66	50.46
C18:3	α-Linoleic	18.53	16.75	19.1	33.72	20.09
C18:3	ɣ-Linoleic	1.17	2.65	3.60	2.01	0.58

[a] Average values of actual values have been used here, NR means not reported.

respectively. A comparison of the properties of HOB produced from hemp seed oil is given in Table 3.

3.3. Biogas

Biogas is another important member of bioenergy. Several feedstocks (animal waste, sewage sludge, crop residue and household organic waste) are used to produce biogas. Energy crops such as maize, are extensively used for biogas production in Germany [123]. Although HB produces higher yield of biomass, yet it has not been extensively explored as a potential feedstock for biogas production compared to maize [20]. HB produces fairly high biogas yield (3066 m^3/ha) as compared with other biomasses like timothy clover grass (2900–4000 m^3/ha) and Jerusalem artichoke (3100–5400 m^3/ha). HB biogas yield is much higher than those of different plant straws [124]. HB is subjected to anaerobic digestion to produced methane. Although both the hemp and maize produce same amount of methane yield/ha, but higher carbohydrate contents and lower amount of lignin make HB an advantageous feedstock for biogas production. However, HB undergoes lower conversion of its carbohydrates into biogas. Thus, it needs considerable attention to select HB as a potential feedstock for methane production. Harvesting of HB also influences its biogas yield. Late harvested HB (during September–October) has shown higher biogas yield (296 GJ/ha) with a HB yield of 14.4 Mg/ha [15]. The cultivation and harvesting of HB should be investigated in detail to find their effects on methane yield [69].

HB requires pretreatment before its use for biogas production. Thus, HB particle size affects methane yield. Mechanical pretreated HB resulted in 21% increase in biogas yield [20] because mechanical pretreatment removes some of the structural resistance. Kreuger et al. [16] found that ground HB stems produced 219 L of methane per kg VS compared with 190 L of methane per kg. VS from chopped HB stems. HB leaves even produced 256 L methane per kg. VS, which was 15–26% higher yield than ground and chopped HB stems. HB leaves contain higher ash content than the stems which equalizes methane yield for both leaves and stems per g of DM [16]. Mechanical pretreated HB yielded 290 ± 13 Ndm^3 of biogas per kg volatile solids (VS). The biogas yield was still lower compared to maize (379 ± 16 Ndm^3/kg VS) due to partial conversion of carbohydrates. This difference in biogas yield, between HB and maize, cannot be associated with their compositions because HB contains more carbohydrates than maize. However, the availability of carbohydrate for anaerobic digestion is crucial. HB possesses a recalcitrant structure that resists against enzymatic activity. Furthermore, C:N ratio plays a significant role in biogas production from HB. HB contains higher C:N ratio (37:1) than 10–30:1 [20]. This higher content of carbon does not get converted into methane due to lower conversion rate [7].

Steam pretreated HB slurry yielded 225 L methane per kg. VS. Holtzapple et al. [125] found that steam pretreatment of HB resulted in smaller particle size that required comparatively less amount of energy than mechanical pretreatment. Contrary to mechanical pretreatment, steam explosion produced higher volume of methane gas. Steam pretreated HB resulted in 13–20% higher methane yield than mechanically pretreated stems. Steam pretreated HB was subjected to co-production of ethanol and methane. This approach resulted in twice the energy yield than of ethanol and methane production alone i.e., in total 171–180 GJ per 10,000 m^2 of agricultural land, based on a hemp biomass yield of 16 Mg DM [16].

3.4. Solid fuel

Hemp can also be used as solid fuel for combustion in boilers as a cheap bioresource. Moisture content (MC) of biomass affects its energy yield, thus, a lower MC value is usually desired. Lower MC also assists to avoid losses in biomass caused by biodegradation. Hemp normally possesses a lower MC with delayed harvesting, however, some of the leaf biomass is also lost. Thus, both of the factors compensate their impacts and resultantly harvesting time becomes insignificant for net energy yield. It is recommended that early harvesting (March–April) should be preferred to use HB as solid fuel, with an average HB yield of 10.91 t DM/ha, and energy yield of 246 GJ/ha [15].

3.5. Biohydrogen

Biohydrogen has gained importance as a green fuel recently due to various advantages [126] such as high energy yield (120 MJ/kg) almost three times higher than fossil fuels [127] and low impact combustion products [128]. Microbial fermentation is commonly employed process to produce hydrogen from LCBs [129,130]. Many researchers have investigated various bacterial species for hydrogen production, and found that thermophiles are advantageous due to their accelerated growth, ability to utilize variety of substrates and high hydrogen yields [131–133]. Thermophilic microorganisms, such as *Thermococcus kodakaraensis* KOD1, *Clostridium thermolacticum*, and *Clostridium thermocellum* JN4, have been investigated for their potential to produce biohydrogen production [134,135]. Moreover, temperature and partial pressure of hydrogen are critical factors for biohydrogen production. Elevated temperature thermodynamically favors the metabolism reactions, and hence, rate of reaction [132,136]. Thermophilic microorganisms are preferred due to specificity for fermentation end products compared to mesophiles [137].

De Vrije et al. [138] reported that *Caldicellulosiruptor saccharolyticus* (an extreme thermophile) yielded the highest concentration of hydrogen under gas sparging environment. It produced 3.6 mol of H_2 per mol of glucose along with some end products like acetate, and mixture of hydrogen and carbon dioxide. Some other strains including *Thermotoga elfii* and a bacterial consortium from Icelandic hot springs had yielded 3.3 and 3.2 mol H_2 mol-glucose^{-1} [130,139]. Almarsdottir et al. [126] investigated production of hydrogen from *C. sativa* using new thermophilic bacterial strain AK_{14} which was similar to *Clostridium thermobutyricum*. The hydrolysate of untreated hemp stem produced 13.5 mmol/L of hydrogen along with some major byproducts (monosugars, acetate and butyrate), and one minor byproduct (ethanol). Pretreatment of hemp leaves with dilute acid (0.75% H_2SO_4) and base (0.75% NaOH) could produce 2 to 3 times higher biohydrogen than the untreated biomass. However, pretreatment did not affect hydrogen yield of HB stems. Selection of acid and base made a little difference using it as pretreatment. Lignin content and/or inefficient pentose fermentation could be the possible reasons for lower H_2 yield from hemp biomass [126].

4. Pakistan perspective

According to Ahmad [140], Pakistan is situated between the latitudes of 23°47′ and 37°04′ North and longitudes of 60°55′ and 77°47′ East, stretching over 1600 km north to south and 885 km east to west. Pakistan has a sub-tropical and semi-arid climate. The annual rainfall in the southern plains is 125 mm while it ranges from 55 to 900 mm in the sub-mountainous and northern plains of the country [140].

Fig. 2. Hemp plants grown wildly in Islamabad (Captured by Shahid Mahmood and Mateen Shafqat on 2011-10-05).

4.1. Hemp production

Hemp grows as a wild plant in the most parts of Pakistan; the Northern Province of Pakistan [141], Gujrat District [142] and is also cultivated in some regions of the Potohar Plateau in the Punjab province of Pakistan due to suitable environmental and soil conditions [13]. It can be found in abundance in all the sectors of Islamabad-capital of Pakistan [143,144] as shown in Fig. 2. Although it grows widely and cultivated in some regions of Pakistan, yet no estimate are available about its production/cultivation throughout the country.

Hemp is locally known as bhang in Pakistan. It is valuable and profitable crop due to several domestic applications. Dried hemp leaves are powdered which is locally called Gharda. This powder is used for cattle treatment against flatulence and abdominal pain. Hemp seeds are used as poultry feed [145]. Hemp oil is a valuable substitute for conventional cooking oil having higher nutritional values [13]. It also possesses narcotic character and is used to prepare hashish or charse locally. Abbas et al. [143] reported that Islamabad was ranked among the cities with highest pollen counts in the world, and hemp was one of the major sources of airborne pollen allergy in Islamabad. According to health ministry, approximately 100,000 people were found victims of pollen allergy during March 15–31, 2011 [146].

4.2. Energy crisis in Pakistan

Pakistan is an agro-economy which is facing economical crisis due to the worst energy shortage [147]. Power load shedding has not only deteriorated national economy, but it also impacted the quality of life in the country [148]. Energy shortage has resulted in a straightaway decrease in national growth rate by 2% during 2009–2010 [149]. Pakistan has produced 65,000 barrels/day of crude oil and 4063 million ft^3/day of natural gas during 2009–2010 which corresponds to 53% of total energy requirements. Other energy resources contribute up to 19% to the total requirements. The current energy supplies and their percentage share are presented in Fig. 3. Total energy demand has been recorded around 62.6 Mtoe during 2008–2009, out of which 27% energy demand has been met through import with an import bill up to US $9 billion. Indigenous conventional energy resources are already exploited at their maximum [150], and in order to meet future growing energy requirements, renewable energy resources need to be given representative share in order to attain Millennium Development Goals. Otherwise, these energy crises will loom in future, and will probably cause economical halt, terrorism and social insecurity in the country Fig. 4.

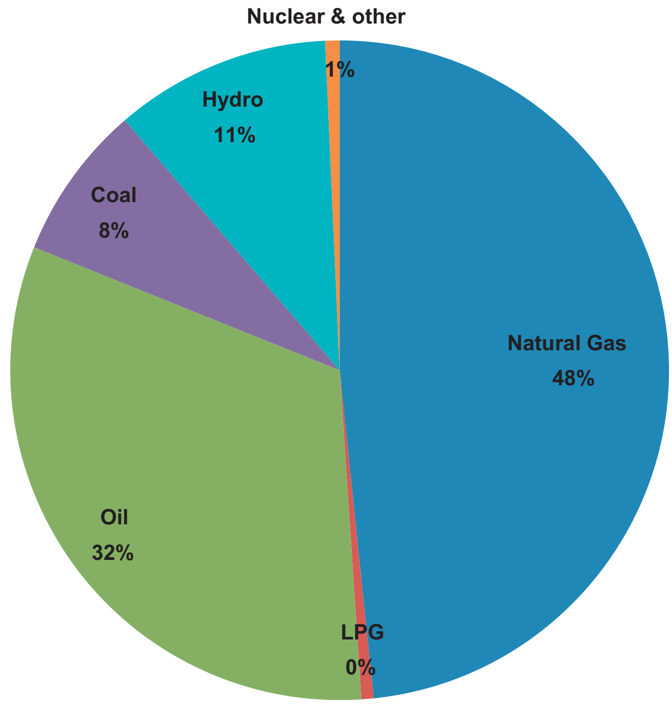

Fig. 3. Pakistan energy supplies during 2008–2009 [150].

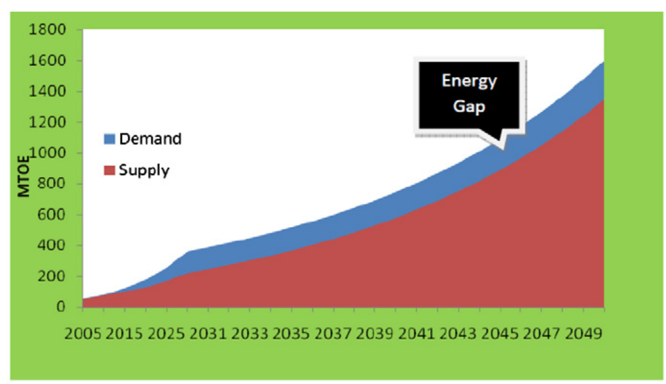

Fig. 4. Projected energy demand and supply in Pakistan for 2005–2050 [adopted from 153].

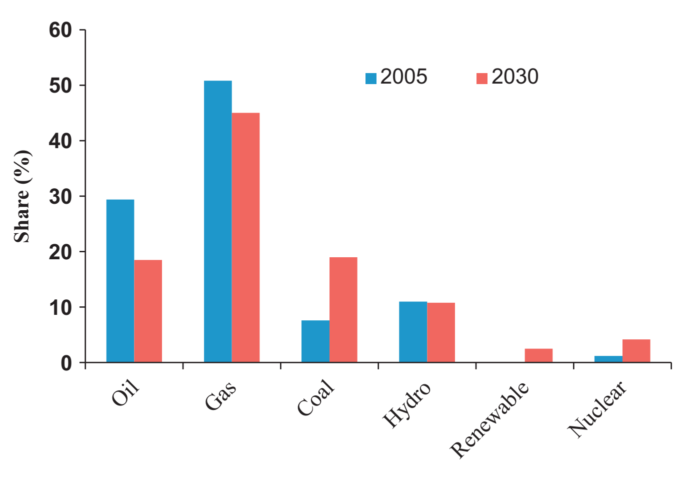

Fig. 5. Projected percentage share of various fuels by 2030 under Pakistan's Energy Security Action Plan (2005–2030) [153].

Sustainable energy supply is necessary in order to improve growth rate and stabilize economy of Pakistan. Pakistan spends almost 20% of its foreign exchange to import fossil fuels [151], whereas conventional fuel export contributes almost 40% to the total imports [152]. It has been estimated that in order to maintain an average GDP around 5.6% between 2011 and 2030, the energy requirements of the country will grow thrice (6.2–18 Mtoe) of the current requirement, and energy imports will grow from 27 to 45% [148]. Pakistan will require approximately 1500 Mtoe energy against estimated available energy of 1286 Mtoe by 2050, thus, leaving an energy gap of 214 Mtoe [153]. Furthermore, Pakistan will confront a 29% energy deficit during the start of next decade [154]. In order to meet current and future energy needs, it is vital to include renewable energy sources in the conventional fuel supply. Among renewable energy resources, biomass could be one of the most viable options for future energy security of Pakistan [149].

The government of Pakistan has decided to increase its renewable energy share from 0 to 2.5% (0–9.2 Mtoe) of its total energy demand by 2030 as shown in Fig. 5. Bioethanol production has been projected to reach 0.288–1.15 million tons by the year 2030 in Pakistan under different scenarios which will save about US $200–400 million. Biogas production will be increased to produce 4000 MW by 2030 under Pakistan Energy Security Plan [153] which will facilitate more than 70% population living in the rural areas of Pakistan [149].

4.3. Economic and environmental benefits of hemp

Hemp is an economical alternative feedstock that can be used for bioenergy production. It shares several economical and environmental advantages with respect to Pakistan. Hemp shows environment friendly attributes throughout its life cycle. In a recent study, it was reported that hemp biomass showed the lowest impact on environment against the parameters such as nutrient depletions, pesticide application, soil compaction and agro-biodiversity. However, it showed medium to low impact for erosion, and medium impact for water consumption and biodiversity [25]. Besides these advantages, hemp is an excellent phytoremediation biomass that has been used to decontaminate soils containing heavy metals [21,155]. These metals usually accumulate in plants biomass, and can be extracted from the ash contents. Residual hemp biomass, obtained after bioenergy extraction, can also be used to prepare biochar that can be applied as soil amendment. This biomass recycling would ensure carbon sequestration in the country.

A recent study reveals that hemp biomass can save 70–255 GJ/ha of energy along with a greenhouse gas saving of 9–28 t CO_2-eq/ha [156]. Moreover, hemp biomass may yield 413 Kg of bioethanol [157], 185 GJ of biogas and 105 GJ of solid fuel [15] on per hectare basis. However, bioelectricity production (based on biogas) faces some limitations due to unfavorable energy and GHG balance [158,159]. The use of hemp seed oil in the production of biodiesel shows minimal impact on environment compared with fossil diesel [160]. These economical and environmental assessments show the feasibility of hemp to be used as a feedstock for bioenergy production in Pakistan. However, further details of economical and environmental analyses and impacts of hemp biomass are given elsewhere in literature [15,156–160]. These studies may involve statistical/mathematical modeling in order to calculate environmental (effect of HB on GHG emissions) and economical (present and future energy dynamics) in Pakistan. Some exemplary studies can be found in the literature [161].

4.4. Hemp bioenergy prospective

Previous discussion shows that Pakistan is facing serious energy crisis which will continue in future as well. Immediate actions, on short term and long term basis, are needed to be taken for energy security to ensure sustainable economic growth in the country. The government of Pakistan has planned to diversify its conventional energy share with sustainable renewable energy by 2.5% [153]. HB has emerged as a cheap and environmental friendly feedstock for bioenergy production within the context of Pakistan. HB is native to the climate of Pakistan, and it grows wildly on a huge area from Punjab to Northern areas. Moreover, excessive HB causes pollen allergy in the occupants, and pose an additional financial burden on the national economy. Thus, HB can be easily converted into a potential energy crop without any major investment. HB has successfully yielded bioethanol, biodiesel, biogas and biohydrogen besides its potential to use it as conventional solid fuel. The further study is required to assess HB cultivation area in Pakistan, and about net energy gain from this biomass. Moreover, life cycle assessment is also required to measure the effect of hemp on greenhouse emissions and/or energy dynamics in Pakistan. These studies require in depth analysis that cannot be covered within the scope of present study. Thus, some exemplary studies can be found in the literature [15,156–161].

5. Conclusions

Pakistan is confronted with the worst ever energy crisis which have put its economic growth and sustainability at stake. On the other hand, energy demand is continuously growing and has caused a huge gap between energy demand and supply. Alternative energy resources, especially biomass, should be considered as a reliable and sustainable option. Industrial hemp is native to Pakistan and it grows wildly on a vast area of Pakistan. HB has proven environment friendly and economical feedstock for various bioenergy options. It can be explored to produce various kinds of biofuels (Bioethanol, biodiesel, biogas and biohydrogen). This biomass feedstock will assist to meet national energy goals set under Pakistan's Energy Security Action Plan (2005–2030) to save US $200–400 million and feeding 4000 MW of energy into the national energy supply line [152].

Acknowledgement

This research was supported by the Advanced Biomass R&D Center(ABC) under the project (ABC-2010-0029728) funded by the Ministry of Education, Science and Technology. Authors are thankful to Mr. Shahid Mahmood and Mateen Shafqat, for capturing pictures of hemp from various sectors of Islamabad.

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